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The experimentally observed flow of plasma ablated by a laser from a planar target resembles the nozzle flow of fluid from a circular orifice. This has implications for experimental simulations of spherical laser fusion pellets using planar targets and affects far field ion measurements in planar geometry experiments.

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ABLATED PLASMA FLOW FROM PLANAR TARGETS

While laser fusion as presently envisioned will use spherical pellets, many experimental investigations of laser-matter interaction are performed on flat targets. There are a number of advantages of planar geometry, including: 1) the ease with which experiments may be conducted when uniform spherical illumination by multiple beams is not required, 2) the accessibility of the rear side of the target (corresponding to the inside of a pellet shell) for diagnostic purposes, and 3) the apparent need for less laser energy than would be required to illuminate the entire surface of a sphere at any given intensity. It is often assumed that planar experiments are nearly one-dimensional, due perhaps to the preponderance of 1-D theory and simulation. One then assumes that physics results obtained on planar targets are scaleable to spherical geometry for large pellets (where the spherical divergence of ablated plasma flow is less important) and at early times (before spherical convergence of the imploding shell is important).

A major difference between planar target and pellet experiments, however, is that there is no edge to the irradiated region on a uniformly irradiated sphere as there is to the finite focal spot on a planar target. This difference has a number of effects on the interaction; for example, it allows lateral transport of energy to areas of target surface outside of the irradiated spot on planar targets. In the present investigation, a different finite laser spot effect is experimentally studied; the divergent flow of ablated plasma away from the target surface is found to resemble the nozzle flow of fluid from a circular orifice. This has three implications for planar target experiments: 1) more laser energy may be required for planar simulations of pellet geometry than one would expect in the absence of the divergent flow, 2) parametric variation of the incident intensity

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by variation of the laser spot size is probably valid only for larger spot sizes, and 3) far field ion diagnostics require a number of channels if results valid over the entire laser focal region are desired.

The experimental arrangement is shown in Fig. 1A. Foil targets are irradiated at 6^{o} angle of incidence by a single beam of the Pharos II Nd (λ_{o} = 1.054 μm) laser system. With incident laser energies between 100 and 200J, incident pulselength of 4 nsec, and irradiated spot diameter (in the near field of an f/6 lens) of $\simeq$0.75 mm full width at half intensity, the incident irradiance is $I_{o} \simeq 3\text{-}6 \times 10^{12}$ W/cm^{2}. A camera with an array of five pinholes (with diameters between 5 and 55 μm) is used to obtain time-integrated images of x-ray emission at 90^{o} to the target normal. The 15 μm beryllium filters used on the camera allow imaging of photons with energy $h\nu > 1$ keV.

For the purposes of this investigation, targets are fabricated with locally deposited tracer material. Circular aluminum spots, approximately 260 μm in diameter and 2 μm thick, are evaporatively coated onto 35 μm thick polystyrene (CH) sheet. Targets are cut from this material and aligned so that 2-4 spots fall within the laser-irradiated region. Since the aluminum is a much stronger emitter than CH of x rays in the spectral band of the pinhole camera, streamlines of material flowing from the aluminum spots at the target surface are identifiable by the track of strong x-ray emission, as seen in Fig. 2A. The perturbation of the flow pattern due to the addition of a second material should be minimal because: 1) there is only a 12% difference between the fully ionized mass density ρ for Al and CH at a given electron density n_e in the blowoff plasma ($\rho \simeq n_e M/Q$, where Q and M are the ion charge and mass, respectively), and 2) the average velocity of ablated ions as determined by Faraday cups is the same for the two materials.

Qualitatively, these streamlines exhibit two properties. First, the angle of a streamline relative to the target normal depends on its point of origin at the target; that is, streamlines emanating from near the center of the x-ray image propagate nearly normal to the target, while those originating near the edge of the image propagate at larger angles. In addition, this angle increases with distance from the target; streamlines, particularly those near the image edge, curve away from the target normal as they propagate away from the target.

Both of these streamline properties would occur for certain classes of steady-state fluid nozzle flows from circular orifices. For example, one may consider the extremely simple case of irrotational flow of a nonviscous compressible fluid from a circular orifice.[1] This potential flow, at least for low mach numbers and nearly paraxial streamlines, is well approximated by the solution of Laplace's equation subject to boundary conditions at the source. Equipotential lines and streamlines for the Laplacian solution are shown in Fig. 2B; the pattern does bear resemblance to the x-ray images. The angle θ between a streamline and the target normal is seen to depend upon the source position r of the streamline in the target plane and upon the distance Z from the target surface. Fixing $Z = 0.75r_o$, where r_o is the orifice radius for the Laplacian flow and the observed image radius for the x-ray data, the dependence of θ upon r (normalized to r_o) is displayed in Fig. 2C. The range of streamline angles is similar for the two cases, though the details of the dependence upon r/r_o may not be. Of course, the simple model chosen does not accurately represent the case of the laser-ablated target, where fluid emerges at low velocity from the "orifice" at the solid surface and is subsequently accelerated to sonic or supersonic speeds. The qualitative similarities between the data and the Laplacian do suggest, however, that some form of steady nozzle flow is present.

The presence of such a flow pattern is not surprising, since: 1) the plasma dimension transverse to the laser axis ($\simeq$1mm) is much greater than the ion-ion collision mean free path ($\simeq$ 1 μm at 0.1 critical density with T $\simeq$ 400 eV as determined from x-ray spectra), and 2) the laser pulselength (4 nsec FWHM) is greater than the sound transit time across the focal radius ($\simeq$2 nsec). The existence of a low density plasma "expansion fan" from planar targets has long been recognized,[2] though detailed 2-D calculations of this flow have only recently been performed.[3] We believe, however, that this is the first reported observa.ion of the effect.

The existence of the divergent flow impacts the ability of planar experiments to adequately simulate the long scalelength plasmas anticipated for large reactor pellets (these scalelengths might be desired in studies of laser absorption, for example). As seen in Fig. 2A, the flow is significantly divergent within a focal spot radius of the target. To produce a plasma with a millimeter scalelength, such as will surround some of the larger pellets,[4] one then requires a multimillimeter laser spot on a planar target. The savings in required laser energy of a planar experiment over a spherical experiment at a given intensity is then less than one might have expected in the absence of the nozzle flow.

In experiments designed to study the dependence of absorption on laser intensity, this variation of plasma scalelength with focal spot size can lead to spurious results. If intensity is varied by changing focal spot size, as is commonly done, observed variations in absorption may be due to changes in plasma scalelength as well as to changes in intensity. As one example, this may have contributed to a short-pulse, higher-intensity result that fractions and angular distributions of absorption and back reflection depend upon focal spot size for fixed irradiance.[5]

This flow also affects experiments on planar targets which simulate the ablative acceleration of pellet shells. With a laser, absorption takes place at a density well below that of the solid and the ablation process must depend upon energy transport between that absorption region and the near-solid ablation region. For a given laser intensity, the rate of mass ablation from the solid surface, the ablation pressure at that surface, and the amount of smoothing of pressure variations due to lateral variations in incident illumination[6] will all depend to some extent on the proximity of the absorption region to the solid. The distance between the two surfaces will, for steady state conditions and a given intensity, tend to an equilibrium position at which the energy transport into the solid is consistent with the convective energy transport of the ablated mass away from the solid. This is referred to as self-regulation of the flow.[2] If one uses a focal spot radius which is comparable to or less than the distance d to which the absorption-ablation separation would tend for a truly 1-D case (i.e. very large focal spots), the nozzle flow will already be divergent at a distance d from the target. As the focal spot radius is further decreased, the absorption surface will move progressively inward toward the target surface. Therefore, if one is varying the focal spot size as a means of studying the parametric variation of ablation parameters with intensity, as is often done, one must be careful that only focal radii significantly larger than d are used; the use of smaller focal spots may lead to results which represent variation with spot size as well as intensity. For 1.06 μm laser intensity of

10^{13} W/cm^2, the distance d is found from computer simulations to be near 100 μm and is observed to increase with laser intensity.[7]

Finally, the fluid flow affects far field particle diagnostics such as ion collectors or plasma calorimeters. Due to the nozzle shape of the collisional plasma flow near the target surface, a fluid velocity direction is imparted to each fluid element. As the density decreases away from the target, the flow must eventually become collisionless, and the material drifting in the direction set by the nozzle expands due to random thermal motion. Since ablation fluid velocities are generally significantly greater than ion thermal velocities, the thermal expansion will not greatly increase the angular range of material flow set by the nozzle. Indeed, the distribution of ablated mass determined from arrays of charge collectors and plasma calorimeters shows that half of the ablated mass appears in a cone about the target normal with 40° half-angle, which is consistent with the angular spread given by the simple model of Fig. 2B.

In addition to determining the angular distribution of ablated mass, the fluid flow impacts ion detector data interpretation in a second way. Except for any smearing due to thermal expansion after the flow becomes collisionless, the nozzle maps regions of target surface into space. That is, a given mass source point on the target surface feeds mass into a finite range of detection solid angles. Conversely, a single ion detector far from the target intercepts only a small solid angle and therefore samples only a portion of the irradiated spot on the target. To experimentally determine parameters averaged over the laser focal spot, then, one must use an array of ion detectors at a variety of angles.

In conclusion, the nozzle flow of ablated material from the surface of a laser-irradiated planar target is experimentally observed for the first time. Its implications for plasma experiments simulating the spherical laser fusion geometry and its effects on far field ion diagnostics are sometimes forgotten, perhaps due to the preponderance of 1-D theory and simulation. As stated earlier, these implications are: 1) that one may require larger focal spots and, therefore, more laser energy for planar simulation of pellet geometry than would be expected in the absence of divergent nozzle flow; 2) that parametric variation of incident intensity by variation of focal spot size will be complicated by spot size effects unless spots much larger than the equilibrium ablation-absorption separation are used; and 3) that arrays of far field ion detectors must be used if measurements are to be representative of the entire focal region. In the present investigation, fluid steamlines were identified by introducing localized sources at the target surface; it should also be noted that the same phenomenon may be observed if localized sources arise due to unintentional effects, such as filamentation of the incident laser beam.[9]

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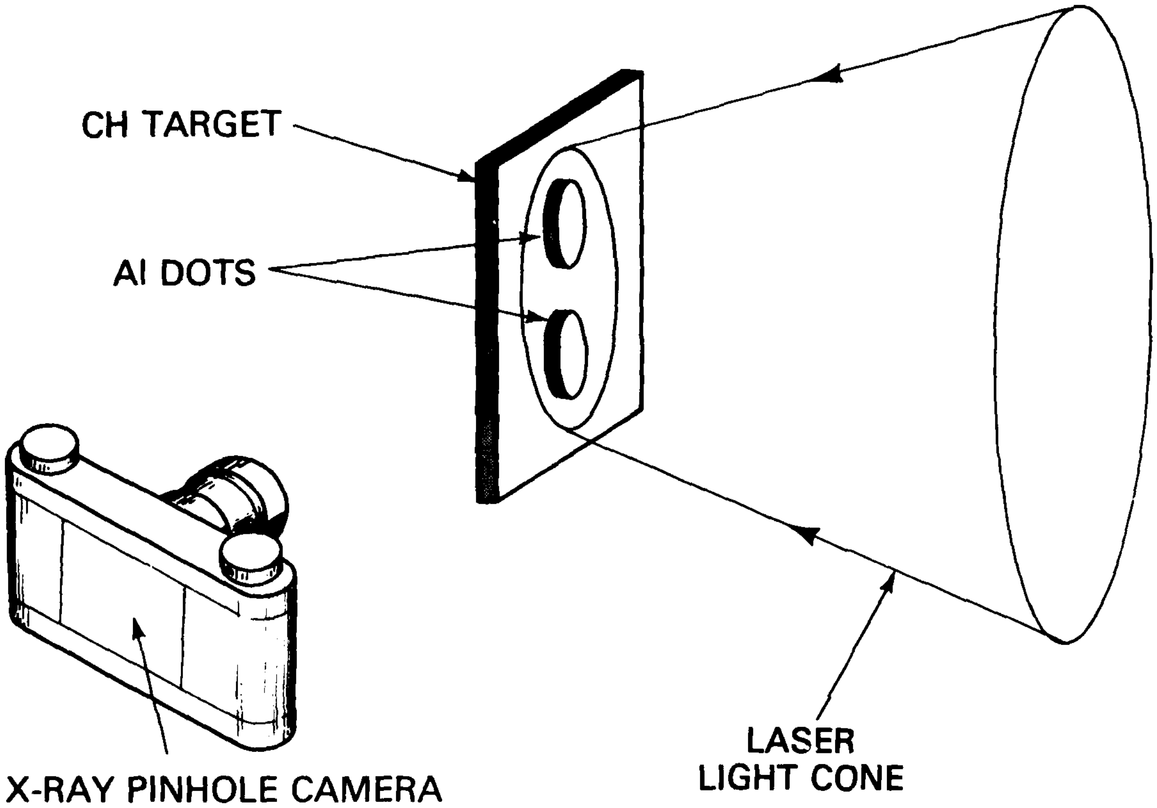

Fig. 1 — Schematic illustration of experimental apparatus

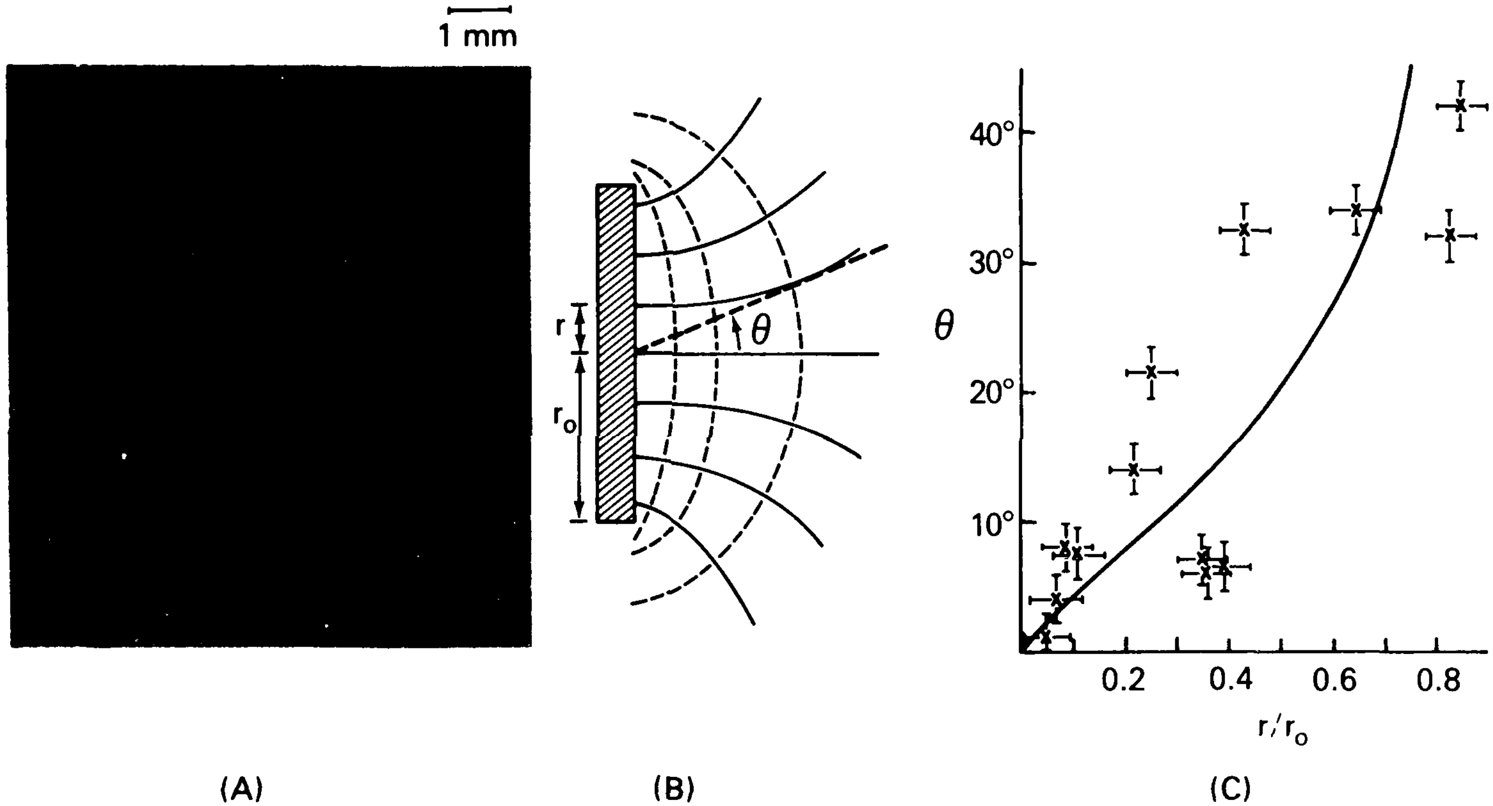

Fig. 2 — (A) Time-integrated images of x-ray emission. Five images correspond to pinhole diameters of 5, 8.5, 13, 28, and 54 μm. Laser is incident from right. (B) Pattern of Laplacian flow from circular orifice. Dotted lines are constant velocity-potential surfaces and solid lines are fluid streamlines. (C) Dependence of streamline angle, θ, relative to target normal (at a distance = 0.75 source radii from the target surface) upon source position in the target plane. Orifice radius is r_o and source is radius r from center. Solid curve is for Laplacian flow pattern from (B), and points (x) with error bars are experimental points from x-ray images such as (A).

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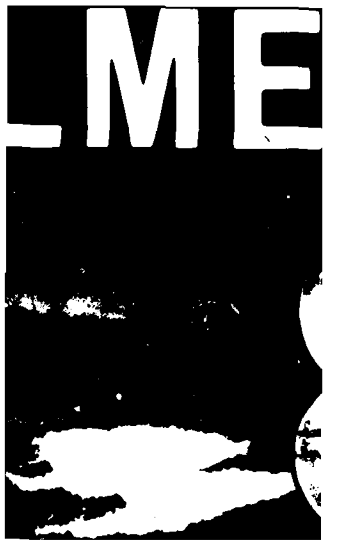
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